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| Title | ON GENERALIZED POWERS-ST\$O\$RMER'S INEQUALITY (Research on structures of operators via methods in geometry and probability theory) |
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| Citation | 数理解析研究所講究録 (2013), 1839: 17-24 |
| Issue Date | 2013-06 |
| URL | http://hdl.handle.net/2433/194950 |
| Right | |
| Type | Departmental Bulletin Paper |
| Textversion | publisher |

ON GENERALIZED POWERS-STØRMER'S INEQUALITY

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ABSTRACT. A generalization of Powers-Størmer's inequality for operator monotone functions on $[0, +\infty)$ and for positive linear functional on general C^* -algebras will be proved. It also will be shown that the generalized Powers-Størmer inequality characterizes the tracial functionals on C^* -algebras.

1. INTRODUCTION

Powers-Størmer's inequality (see, for example, [16, Lemma 2.4], [4, Theorem 11.19]) asserts that for $s \in [0, 1]$ the following inequality

$$(1) \quad 2 \operatorname{Tr}(A^s B^{1-s}) \geq \operatorname{Tr}(A + B - |A - B|)$$

holds for any pair of positive matrices A, B . This is a key inequality to prove the upper bound of Chernoff bound, in quantum hypothesis testing theory [1]. This inequality was first proven in [1], using an integral representation of the function t^s . After that, N. Ozawa gave a much simpler proof for the same inequality, using fact that for $s \in [0, 1]$ function $f(t) = t^s$ ($t \in [0, +\infty)$) is an operator monotone ([11, Proposition 1.1]). Recently, Y. Ogata in [13] extended this inequality to standard von Neumann algebras. The motivation of this paper is that if the function $f(t) = t^s$ is replaced by another operator monotone function (this class is intensively studied, see [8][14]), then $\operatorname{Tr}(A + B - |A - B|)$ may get smaller upper bound than what is used in quantum hypothesis testing. Based on N. Ozawa's proof we formulate Powers-Størmer's inequality for an arbitrary operator monotone function on $[0, +\infty)$ in the context of general C^* -algebras.

2. DOUBLE PILING STRUCTURES FOR MATRIX FUNCTIONS

Throughout this note, M_n stands for the algebra of all $n \times n$ matrices, M_n^+ denote the set of positive semi-definite matrices. We call a function

^{1A}Research partially supported by the JSPS grant for Scientific Research No. 20540220.

Date: 13, Feb., 2013.

2000 Mathematics Subject Classification. 46L30, 15A45.

Key words and phrases. Powers-Størmer's inequality, trace, positive functional, C^* -algebras.

f *matrix convex of order n* or *n -convex* in short (resp. *matrix concave of order n* or *n -concave*) whenever the inequality

$$f(\lambda A + (1 - \lambda)B) \leq \lambda f(A) + (1 - \lambda)f(B), \quad \lambda \in [0, 1]$$

(resp. $f(\lambda A + (1 - \lambda)B) \geq \lambda f(A) + (1 - \lambda)f(B)$, $\lambda \in [0, 1]$) holds for every pair of selfadjoint matrices $A, B \in M_n$ such that all eigenvalues of A and B are contained in I . *Matrix monotone functions* on I are similarly defined as the inequality

$$A \leq B \implies f(A) \leq f(B)$$

for any pair of selfadjoint matrices $A, B \in M_n$ such that $A \leq B$ and all eigenvalues of A and B are contained in I . We call a function f *operator convex* (resp. *operator concave*) if for each $k \in \mathbb{N}$, f is k -convex (resp. k -concave) and *operator monotone* if for each $k \in \mathbb{N}$ f is k -monotone.

In [15] Tomiyama and the author discussed about the following 3 assertions at each level n among them in order to see clear insight of the double piling structure of matrix monotone functions and of matrix convex functions:

Theorem 2.1. *Let $n \in \mathbb{N}$ and $f : [0, \alpha) \rightarrow \mathbb{R}$ and consider the following assertions.*

- (i) $f(0) \leq 0$ and f is n -convex in $[0, \alpha)$,
- (ii) For each matrix a with its spectrum in $[0, \alpha)$ and a contraction c in the matrix algebra M_n ,

$$f(c^*ac) \leq c^*f(a)c,$$

- (iii) The function $\frac{f(t)}{t}$ ($= g(t)$) is n -monotone in $(0, \alpha)$.

Then we have

$$(i)_{n+1} \prec (ii)_n \sim (iii)_n \prec (i)_{\lfloor \frac{n}{2} \rfloor},$$

where the denotation $(A)_m \prec (B)_n$ means that “if (A) holds for the matrix algebra M_m , then (B) holds for the matrix algebra M_n ”.

The following result is proved in [5].

Lemma 2.1. *Let f be a strictly positive, continuous function on $[0, \infty)$. If the function f is $2n$ -monotone, then for any positive semi-definite A and a contraction C in M_n we have*

$$C^*f(A)C \leq f(C^*AC).$$

The following result is essentially proved in [7, Theorem 2.4], but for the reader's convenience we will include a proof.

Proposition 2.1. *Let f be a strictly positive, continuous function on $[0, \infty)$. If f is $2n$ -monotone, the function $g(t) = \frac{t}{f(t)}$ is n -monotone on $[0, \infty)$.*

Proof. Let A, B be positive matrices in M_n such that $0 < A \leq B$.

Let $C = B^{-\frac{1}{2}}A^{\frac{1}{2}}$. Then $\|C\| \leq 1$. Since f is $2n$ -monotone, $-f$ satisfies the Jensen type inequality from Lemma 2.1, that is,

$$\begin{aligned} -f(A) &= -f(C^*BC) \leq -C^*f(B)C \\ -f(A) &\leq -A^{\frac{1}{2}}B^{-\frac{1}{2}}f(B)B^{-\frac{1}{2}}A^{\frac{1}{2}} \\ -A^{-\frac{1}{2}}f(A)A^{-\frac{1}{2}} &\leq -B^{-\frac{1}{2}}f(B)B^{-\frac{1}{2}} \\ -A^{-1}f(A) &\leq -B^{-1}f(B) \end{aligned}$$

Therefore, since $-1/t$ is operator monotone, $-1/(-f(t)/t) = t/f(t)$ is n -monotone. \square

Remark 1. The condition of $2n$ -monotonicity of f is needed to guarantee the n -monotonicity of g . Indeed, it is well-known that t^3 is monotone, but not 2-monotone. In this case the function $g(t) = \frac{t}{t^3} = \frac{1}{t^2}$ is obviously not 1-monotone.

Corollary 2.1. *Let f be a $2n$ -monotone, continuous function on $[0, \infty)$ such that $f((0, \infty)) \subset (0, \infty)$, and let g be a Borel function on $[0, \infty)$ defined by $g(t) = \begin{cases} \frac{t}{f(t)} & (t \in (0, \infty)) \\ 0 & (t = 0) \end{cases}$. Then for any pair of positive matrices $A, B \in M_n$ with $A \leq B$, $g(A) \leq g(B)$.*

Similarly, we can get the concave version of the above observation [10].

Theorem 2.2. *For $n \in \mathbb{N}$ and $f : [0, \alpha) \rightarrow \mathbb{R}$ we consider the following assertions:*

- (iv) $f(0) \geq 0$ and f is n -concave in $[0, \alpha)$,
- (v) For each matrix a with spectrum in $[0, \alpha)$ and a contraction c in the matrix algebra M_n ,

$$f(c^*ac) \geq c^*f(a)c,$$

- (vi) The function $\frac{t}{f(t)}$ is n -monotone in $(0, \alpha)$.

We can show that

$$(iv)_{n+1} \prec (v)_n \sim (vi)_n \prec (iv)_{[\frac{n}{2}]}$$

3. GENERALIZED POWERS-STØRMER'S INEQUALITY

In this section we investigate the generalized Powers-Størmer inequality from the point of matrix functions. Note that the $2n$ -monotonicity of a function f on $[0, \infty)$ implies the n -concavity of f by [2, Theorem V.2.5].

Theorem 3.1. *Let Tr be the canonical trace on M_n and f be a $(n+1)$ -concave (or $2n$ -monotone) function on $[0, \infty)$ such that $f((0, \infty)) \subset (0, \infty)$. Then for any pair of positive matrices $A, B \in M_n$*

$$(2) \quad \text{Tr}(A) + \text{Tr}(B) - \text{Tr}(|A - B|) \leq 2 \text{Tr}(f(A)^{\frac{1}{2}} g(B) f(A)^{\frac{1}{2}}),$$

$$\text{where } g(t) = \begin{cases} \frac{t}{f(t)} & (t \in (0, \infty)) \\ 0 & (t = 0) \end{cases}.$$

Proof. Note that we know that a function g is n -monotone from Corollary 2.1 and Theorem 2.2.

Let A, B be any positive matrices in M_n .

For operator $(A - B)$ let us denote by $P = (A - B)^+$ and $Q = (A - B)^-$ its positive and negative part, respectively. Then we have

$$(3) \quad A - B = P - Q \quad \text{and} \quad |A - B| = P + Q,$$

from that it follows that

$$(4) \quad A + Q = B + P.$$

On account of (4) the inequality (2) is equivalent to the following

$$\text{Tr}(A) - \text{Tr}(f(A)^{\frac{1}{2}} g(B) f(A)^{\frac{1}{2}}) \leq \text{Tr}(P).$$

Since $B + P \geq B \geq 0$ and $B + P = A + Q \geq A \geq 0$ and g is n -monotone, we have $g(A) \leq g(B + P)$ and

$$\begin{aligned} & \text{Tr}(A) - \text{Tr}(f(A)^{\frac{1}{2}} g(B) f(A)^{\frac{1}{2}}) \\ &= \text{Tr}(f(A)^{\frac{1}{2}} g(A) f(A)^{\frac{1}{2}}) - \text{Tr}(f(A)^{\frac{1}{2}} g(B) f(A)^{\frac{1}{2}}) \\ &\leq \text{Tr}(f(A)^{\frac{1}{2}} g(B + P) f(A)^{\frac{1}{2}}) - \text{Tr}(f(A)^{\frac{1}{2}} g(B) f(A)^{\frac{1}{2}}) \\ &= \text{Tr}(f(A)^{\frac{1}{2}} (g(B + P) - g(B)) f(A)^{\frac{1}{2}}) \\ &\leq \text{Tr}(f(B + P)^{\frac{1}{2}} (g(B + P) - g(B)) f(B + P)^{\frac{1}{2}}) \\ &= \text{Tr}(f(B + P)^{\frac{1}{2}} g(B + P) f(B + P)^{\frac{1}{2}}) \\ &\quad - \text{Tr}(f(B + P)^{\frac{1}{2}} g(B) f(B + P)^{\frac{1}{2}}) \\ &\leq \text{Tr}(B + P) - \text{Tr}(f(B)^{\frac{1}{2}} g(B) f(B)^{\frac{1}{2}}) \\ &= \text{Tr}(B + P) - \text{Tr}(B) \\ &= \text{Tr}(P). \end{aligned}$$

Hence, we have the conclusion. \square

Corollary 3.1. *Let f be an operator monotone function on $[0, \infty)$ such that $f((0, \infty)) \subset (0, \infty)$. Then for any pair of positive matrices $A, B \in M_n$*

$$(5) \quad \text{Tr}(A) + \text{Tr}(B) - \text{Tr}(|A - B|) \leq 2 \text{Tr}(f(A)^{\frac{1}{2}} g(B) f(A)^{\frac{1}{2}}),$$

$$\text{where } g(t) = \begin{cases} \frac{t}{f(t)} & (t \in (0, \infty)) \\ 0 & (t = 0) \end{cases}.$$

Note that the operator monotonicity is equivalent to the operator concavity in the case that $f([0, \infty)) \subset [0, \infty)$ [2, Theorem V. 2.5].

Corollary 3.2. [1, Theorem 1] *Let A and B be positive matrices, then for all $s \in [0, 1]$*

$$\text{Tr}(A + B - |A - B|) \leq \text{Tr}(A^s B^{1-s}).$$

Remark 2. As pointed in Proposition 2.1, 2-monotonicity of f is needed to guarantee the inequality (2). Indeed, let $f(t) = t^3$ and $n = 1$. Then, for any $a, b \in (0, \infty)$, the inequality (2) would imply

$$a \leq f(a)^{\frac{1}{2}} g(b) f(a)^{\frac{1}{2}},$$

that is,

$$\frac{a}{f(a)} \leq \frac{b}{f(b)}.$$

Since $\frac{t}{f(t)}$ is, however, not 1-monotone, the latter inequality is impossible.

Remark 3. For matrices $A, B \in M_n^+$ let us denote

$$(6) \quad Q(A, B) = \min_{s \in [0, 1]} \text{Tr}(A^{(1-s)/2} B^s A^{(1-s)/2})$$

and

$$(7) \quad Q_{\mathcal{F}_{2n}}(A, B) = \inf_{f \in \mathcal{F}_{2n}} \text{Tr}(f(A)^{\frac{1}{2}} g(B) f(A)^{\frac{1}{2}}),$$

where \mathcal{F}_{2n} is the set of all $2n$ -monotone functions on $[0, +\infty)$ satisfy condition of the Theorem 3.1 and $g(t) = t f(t)^{-1}$ ($t \in [0, +\infty)$).

Since the class of $2n$ -monotone functions is large enough [14], we know that $Q_{\mathcal{F}_{2n}}(A, B) \leq Q(A, B)$. Hence, we hope on finding another $2n$ -monotone function f on $[0, +\infty)$ such that

$$(8) \quad \text{Tr}(f(A)^{\frac{1}{2}} g(B) f(A)^{\frac{1}{2}}) < Q(A, B).$$

If we can find such a function, then we may get smaller upper bound than what is used in quantum hypothesis testing [1]. For example, considering the trace distance $T(A, B) = \frac{\text{Tr}(|A - B|)}{2}$, we might have the following better estimate

$$\frac{1}{2} \text{Tr}(A+B) - Q_{\mathcal{F}_{2n}}(A, B) \leq T(A, B) \leq \sqrt{\left\{\frac{1}{2} \text{Tr}(A+B)\right\}^2 - Q_{\mathcal{F}_{2n}}(A, B)^2}.$$

(See the estimate (6) in [1].)

4. CHARACTERIZATIONS OF THE TRACE PROPERTY

In this section the generalized Powers-Størmer inequality in the previous section implies the trace property for a positive linear functional on operator algebras.

Lemma 4.1. *Let φ be a positive linear functional on M_n and f be a continuous function on $[0, \infty)$ such that $f(0) = 0$ and $f((0, \infty)) \subset (0, \infty)$. If the following inequality*

$$(9) \quad \varphi(A+B) - \varphi(|A-B|) \leq 2\varphi(f(A)^{\frac{1}{2}}g(B)f(A)^{\frac{1}{2}})$$

holds true for all $A, B \in M_n^+$, then φ should be a positive scalar multiple of the canonical trace Tr on M_n , where $g(t) = \begin{cases} \frac{t}{f(t)} & (t \in (0, \infty)) \\ 0 & (t = 0) \end{cases}$.

Theorem 4.1. *Let φ be a positive normal linear functional on a von Neumann algebra \mathcal{M} and f be a continuous function on $[0, \infty)$ such that $f(0) = 0$ and $f((0, \infty)) \subset (0, \infty)$. If the following inequality*

$$(10) \quad \varphi(A) + \varphi(B) - \varphi(|A-B|) \leq 2\varphi(f(A)^{\frac{1}{2}}g(B)f(A)^{\frac{1}{2}})$$

holds true for any pair $A, B \in \mathcal{M}^+$, then φ is a trace, where $g(t) = \begin{cases} \frac{t}{f(t)} & (t \in (0, \infty)) \\ 0 & (t = 0) \end{cases}$.

Corollary 4.1. *Let φ be a positive linear functional on a C^* -algebra \mathcal{A} and f be a continuous function on $[0, \infty)$ such that $f(0) = 0$ and $f((0, \infty)) \subset (0, \infty)$. If the following inequality*

$$(11) \quad \varphi(A) + \varphi(B) - \varphi(|A-B|) \leq 2\varphi(f(A)^{\frac{1}{2}}g(B)f(A)^{\frac{1}{2}})$$

holds true for any pair $A, B \in \mathcal{A}^+$, then φ is a tracial functional, where $g(t) = \begin{cases} \frac{t}{f(t)} & (t \in (0, \infty)) \\ 0 & (t = 0) \end{cases}$.

Remark 4. Let \mathcal{A} be a von Neumann algebra and φ be a positive normal linear functional on \mathcal{A} . The set $P(\mathcal{A})$ of all orthogonal projections from \mathcal{A} is enough as a testing space for some inequality to characterize

the trace property of φ (see [3]). But, in the case of the inequality (10) the set $P(\mathcal{A})$ is not enough as a testing set.

Indeed, let P, Q be arbitrary orthogonal projections from a von Neumann algebra \mathcal{M} . Since $Q \geq P \wedge Q$ it follows that $PQP \geq P(P \wedge Q)P = P \wedge Q$. So $PQP \geq P \wedge Q$ holds for any pair of projections. From that it follows

$$\varphi(P + Q - |P - Q|) = 2\varphi(P \wedge Q) \leq 2\varphi(PQP) = 2\varphi(f(P)^{\frac{1}{2}}g(Q)f(P)^{\frac{1}{2}})$$

whenever φ is an arbitrary positive linear functional on \mathcal{M} .

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